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Sukatani revisited: on the performance of nine-year-old solar home systems and street lighting systems in Indonesia

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Abstract

In 1988, 86 solar home systems, SHS, and 15 street lighting systems, SLS, were installed in the village of Sukatani in the province of West Java of Indonesia. The systems have a PV array of 80 Wp.

In this paper we analyse the performance of these systems. For this purpose we use monitoring data and data from field surveys recorded in the period 1988–1993 and data collected in a field survey in 1997. This survey comprised both technical measurements on 62 solar home systems and interviews with 22 users of these systems.

We found that, although the failure rate of street lighting systems is high, the villagers have a positive opinion about these systems.

Further, we found that technically the solar home systems performed well. The users are satisfied about the performance. However, in the course of time the configuration of the SHS has changed: villagers have replaced most of the strip lights with cheap home-made candescent lamps and have replaced the initially-installed 100 Ah capacity solar batteries with cheaper locally produced 70 Ah capacity car batteries.

From an analysis of monitoring data we found that the average irradiation in Sukatani is 4.2 kW/m^2/day, which is a common value for Indonesia, but more than expected in 1988 when the systems were installed (3.5 kWh/m^2/day). Furthermore, we found that daily

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Nomenclature

A	diameter of a cable [m^2]
A_{PV}	cell area of a PV array [m^2]
$C_{I,nom}$	nominal battery capacity (at I_{100}) [Ah]
$DDOD$	daily depth of discharge [%]
E_D	electricity demand [Wh/day]
$E_{I,A}$	electricity from array [Ah/day]
$E_{I,LOAD}$	electricity to load [Ah/day]
E_{PV}	electricity supplied by a PV system [Wh/day]
$G_{i,ref}$ (G)	irradiance in the array plane [W/m^2/day]
$H_{i,ref}$(H)	irradiation in the array plane [kWh/m^2/day]
I_A	current from the array [A]
I_{LOAD}	Current to the load [A]
k	temperature factor [$^\circ Cm^2/W$]
L	length of cables [m]
$P_{A,nom}$	nominal array power [Wp]
PR	performance ratio [%]
PR_I	performance ratio based on current measurements [%]
R	cable resistance [Ωm]
SF	solar fraction [%]
T_A	ambient temperature [°C]
T_B	temperature in the battery box [°C]
T_M	module temperature [°C]
UE	unused energy [%]
V_B	battery voltage [V]
$V_{TB,mean}$	mean battery voltage at charging [V]
$V_{FB,mean}$	mean battery voltage at discharging [V]
Greek symbols	
$\eta_{I,B}$	battery efficiency [%]
Δp_{cable}	power loss due to cables [W]
BCR	battery charge regulator
KUD	Kooperasi Unit Desa, i.e. village co-operative
IDR	Indonesian Rupiah
SB	small bulb
SHS	solar home system
SLS	street lighting system
TCU	time control unit

electricity consumption per SHS can be as high as 25 Ah/day. Average values, however, range from 8.8 to 14.8 Ah/day, which is 15–50% below the daily load used in the design calculations (17.4 Ah/day). However, the average daily electricity consumption is close to the recommended value on the instruction sheets given to the users of the SHS. Because of

the low demand of electricity the average performance ratio is 49%. By means of an energy loss analysis of the PV systems we found that 15% of the theoretically available energy from the array cannot be fed in the battery because it is fully charged.

The replacement of 100 Ah batteries by 70 Ah batteries was justified on the grounds of the low electricity consumption of the SHS users in the period 1988–1993. On the basis of field surveys we found that the average lifetime of the 100 Ah and 70 Ah batteries is 4 and 3.5 years, respectively. The realized battery lifetime is rather long compared with other SHS projects in the world.

While the average battery size in Sukatani decreased in course of time, we found on the basis of interviews with users of SHS that the average daily electricity consumption increased. We found a value of 18 Ah/day in 1997.

Furthermore, the spread in the demand of electricity in 1997 and the use of other than initially-installed appliances, such as small incandesent bulbs and intercoms, indicates the need for a broad offer of system sizes and low power appliances. By means of design calculations we found that PV arrays in the range of 35–130 Wp are needed to satisfy different demand patterns.

We conclude that monitoring by means of data loggers is a useful approach to allow the analysis of the long-term system performance. To increase the statistical reliability of results, monitoring should be supplemented by field measurements and interviews with users. However, due to the deviation between real and narrated experiences, interviews alone may not be sufficient to assess an SHS project.

1. Introduction

In rural areas where no electricity grid is available, electricity can be supplied by small photovoltaic PV systems such as solar home systems, SHS, and street lighting systems, SLS. Despite the large number of SHS installed world wide, roughly 500,000 in 1996 [1], and the promising future for this technology [2], only a few attempts have been made to investigate and evaluate the performance of this type of PV system in the field, for example [3,4,5,6]. Thus, measured figures regarding, for example, the electricity consumption of the users of these systems, system performance and failure rates of components are rarely available. Investigation on evaluation of the performance of the systems can show whether they live up to expectations and if not, why not. Investigations can also reveal how the performance can be improved.

Small PV systems for single household electrification, solar home systems, SHS, and street lighting systems, SLS, were introduced to Indonesia in 1988. The project was based in the village of Sukatani in West-Java. The project comprised 86 SHS and 15 SLS. The Sukatani-project stimulated the widespread use of SHS in Indonesia [2]. It is estimated that from 1988 to 1996, 50,000 SHS were installed in Indonesia [7,8].

The pilot project in Sukatani was accompanied by a monitoring programme

which was executed by the Agency for the Assessment and Implementation of Technology, LSDE–BPPT (Jakarta) and PT R&S Renewable Energy Systems (Jakarta). The programme comprised measurements with data loggers [9,10,11] and the establishment of periodic site surveys of technical [12] and social aspects [13,14,15]. Results were presented at two workshops, one in 1989 [16,17,18] and the other in 1993 [19,20,21,22]. The latter resulted in two international publications [23,24] of a descriptive character.

The information mentioned consists largely of measurement reports containing data which have not yet been analysed profoundly. The long-term development of the project is not evaluated in these reports. Furthermore, some of the reports were written in the Indonesian language or had a restricted distribution. For this reason information is not easily accessible to a broad public. Hence, in order to supplement the, as yet, limited field experiences with SHS, the authors consider it sensible to turn their attention to this project stimulated by its relatively long history.

This paper is the result of a close co-operation between LSDE–BPPT (Jakarta, Indonesia) and Utrecht University (Utrecht, the Netherlands). In the period October 1997 to January 1998 the first author gathered reports and monitoring data recorded earlier, and with the assistance of LSDE–BPPT collected new data in the field in Sukatani by performing technical measurements on the PV systems and by analysing questionnaires that were completed by the users of SHS.

This paper has two objectives. The first one is to investigate the operation of the PV systems in Sukatani. We do this by surveying the condition of the PV systems, by drawing up an inventory of users' experiences, and by presenting and interpreting the energy performance of the PV systems. The second objective is to assess both the manner of data collection and the approaches to analyse the data. This can serve the development of improved methods for the appraisal of SHS projects.

According to Cabraal et al. [2], technical, financial, infrastructural and institutional aspects affect the successful implementation and use of SHS. Because acceptance of the new technology and adaptation of the user to this new technology are key factors for successful application [1,25,26], we can add a fifth dimension, namely social aspects. Actually, the interrelated influence of these five aspects requires an interdisciplinairy view of the analysis of SHS projects. Therefore, while focusing on the technical aspects of the SHS and SLS in Sukatani we will keep an eye on the social, financial, infrastructural and to a lesser extent institutional aspects of the operation of these systems as well.

In our opinion the pilot project in Sukatani is primarily a model project. The SHS project in Sukatani was executed under rather specific circumstances, as the technical functioning of the systems was intensively controlled and the users were instructed thoroughly about the correct use of the systems. Moreover, the price that the users pay for the generated electricity is remarkably low. Nevertheless, it is very attractive to investigate the performance of this project for two reasons: (1) it is known as the best-case project in Indonesia, which may indicate the limit of good performance of small solar PV systems in the rural area, and (2) the 9-year old systems provide a good opportunity to investigate their long-term performance and endurance. The latter issue compensates for the fact that the design of this

SHS is old-fashioned and does not represent SHS which comply with the standards nowadays.

The following subjects are dealt with in this paper. To start with, we present the general outline of the project in Sukatani in section 2. Subsequently, in section 3 we formulate the research questions. In section 4 we describe the measurements. Next, in sections 5 and 6, we present the results of field surveys for SLS and SHS, respectively. In section 7 results are presented from an analysis of monitoring data. In section 8, we discuss the results and draw our conclusions on, firstly, the performance of the PV systems and, secondly,the best approaches to collect data and to analyse the performance when investigating these type of systems.

2. Description of the PV project in Sukatani

Sukatani is a small village located 110 km south-east of Jakarta. It is located at 7° S and 107° E at an altitude of 800 m. In 1987 it was selected for a pilot project with small PV systems [27]. The project was accomplished by co-operation between R&S Renewable Energy Systems (now Shell Solar Energy), the Agency for the Assessment and Implementation of Technology of Indonesia (BPPT), and the Directorate General of International Co-operation of the Netherlands (DGIS).

Sukatani was selected on the basis of the following criteria [27]. Because of the demonstrative character of the project and the planned research with the project, the site had to be accessible. Further, the climate had to be suitable for PV systems. The village should not be connected to the electricity grid of the PLN utility[1]. Moreover, the local people should be interested.

In Sukatani 75% of the 400 or so households showed interest in an SHS and were willing to pay [16]. The number of SHS that could be installed depended on the availability of funding. In November 1988, 86 SHS and 15 SLS were installed. Hence, 70% of the households in Sukatani which initially showed interest in obtaining a system did not receive one[2].

2.1. System design

The SHS and SLS in Sukatani were designed by R&S Renewable Energy Systems. They design systems by calculating current and charge flows. The design calculations were based on limited information concerning the available irradiation and on assumptions regarding the electricity consumption of the villagers. The irradiation was estimated at 3.5 kWh/m^2/day on the basis of data

[1] In general, the widely scattered houses in Indonesian agricultural villages lead to high installation and distribution costs if they are linked to a conventional electricity grid [2]. Under these conditions decentralised electricity sources can be a cheaper option. For instance, in Sukatani, distances from the nearest neighbour vary between a few metres and 1000 m.

[2] In 1996, 30 additional systems consisting of a 44 Wp a-Si PV module and a 75 Ah battery were installed.

Table 1
Original system design of the SHS and SLS in Sukatani

Type	Initial system components	Initial appliances (nominal power)	Daily design load (at 12.5 V)[a]
SHS	2 PV panels (40 Wp) 1 battery (100 Ah) 1 battery charge regulator cables	1 strip light (10 W) 2 strip lights (6 W) 1 black and white TV (14 W) 1 radio (7 W) 1 socket	216 WH[b] (17.3 Ah)
SLS	2 PV panels (40 Wp) 2 batteries (100 Ah/bat) 1 time control unit cables	1 low pressure sodium light (18 W)	180 Wh (14.4 Ah)

[a] See section 6.2, for an explanation of why 12.5 V was used for the system voltage instead of the usual 12 V.
[b] This value is used for a full set of appliances comprising a TV and radio.

from the Pakuwon weather station and short-lived measurements in Sukatani. A daily load of 216 Wh/day, see Table 1, consisting of three strip lights, a radio and a TV set was used in the design calculations. Further, for the SHS and the SLS a battery autonomy of 4 and 10 days, respectively, was required. The maximum permissible discharge capacity was set at 70% of the nominal capacity. These conditions led to the system configurations presented in Table 1.

The following components were used in the SHS and SLS.

2.1.1. PV modules

The PV modules are of the type RSM40 produced by R&S Renewable Energy Systems. They consist of 36 semi-crystalline silicon cells of 0.01 m^2 in series. The nominal power is 40 Wp which results in an STC (cell-based) efficiency of 11.1%. The temperature coefficient in the MPP is −0.4%/°C [28]. The technical lifetime of the PV modules is assumed to be 20 yrs.

2.1.2. Batteries

The batteries in the SHS are of the type Varta 82000. They are flooded flat plate lead-acid batteries with a low antimony content. They are designed for shallow cyclic operation in consumer applications like solar energy systems. The manufacturer specifies a nominal capacity $C_{\mathrm{I,nom}}$ at I_{100} of 100 Ah[3]. The technical lifetime of the batteries is specified by the number of cycles of 10% daily depth of discharge (*DDOD*). The lifetime is 1600 cycles at 20°C and 800 cycles at 30°C

[3] Normally, the Varta batteries are filled with an electrolyte with a density of 1.26 kg/l, $C_{\mathrm{I,nom}}$ is 100 Ah. In Indonesia a density of 1.23 kg/l is used so that the real capacity $C_{\mathrm{I,nom}}$ is 93 Ah [29]. The reason for using a lower electrolyte density than usual is to try to reduce grid corrosion [3].

[29]. Assuming one such cycle a day, the lifetime is about 4.5 and 2.5 yrs for 1600 and 800 cycles, respectively.

In the SLS other types of flat plate lead-acid batteries have been installed besides the Varta 82000, namely the TV Marina produced by Anker ($C_{\mathrm{I,nom}} = 105$ Ah) and a battery of 100 Ah of Tudor.

2.1.3. Battery charge regulator

The battery charge regulator, BCR, is of the type BAS 6.12 produced by R&S Renewable Energy Systems. It is a series-regulated BCR which compensates internally for the battery temperature. The set points of the BCR are adjusted at 20°C and specified thus: 11.6 V for the deep-discharge-protection voltage, 12.2 V for the discharge-reconnect voltage, 14.2 V for the overcharge-protection voltage, and 13.6 V for the charge-reconnect voltage.

According to the manufacturer the setpoints of each BCR have been controlled before the devices were sent to Indonesia. The colour of an LED indicates whether electricity is available in the battery; red means that the voltage is below the deep-discharge-protection voltage, indicating that no electricity should be used. The technical lifetime of the BCR is assumed to be 10 yrs.

2.1.4. Time control unit

The time control unit, TCU, of the SLS consists of a timer connected to a series-regulated BCR with compensation for the battery temperature. This BCR applies a less advanced regulation to the currents in the PV system than the device installed in the SHS.

2.1.5. Cables

The cables used have a diameter of 2.5 mm^2. The cable length from the PV array to the BCR or TCU is 12–14 m for an SHS and 4 m for an SLS. The wires that connect the appliances to the BCR or the TCU are 4–10 m long in the case of SHS and 4 m long in the case of SLS.

2.2. Installation of the system

In each system the PV modules are installed at the top of a 4-metre-high pole. The orientation is north at a tilt angle of 10°. The main reason for tilting the modules is to let them be cleaned by rain showers. Namely, due to the length of the pole, installed PV modules are not accessible to clean them manually. The enhancement of the in-plane irradiance by tilting the PV panel is a minor effect. In the case of SHS, the BCR hangs on the wall above the battery. The battery is placed in a wooden box with a lid. The battery box stands on the floor or a small table. In the case of SLS, the TCU is located in a locked iron battery box which hangs on the pole. A lamp is mounted on the pole as well.

2.3. The instructions for the users

When households acquired the SHS, the users received training and an instruction sheet about the usage and maintenance of an SHS. This sheet [10] recommends a daily electricity consumption of at most 125 Wh/day (10 Ah/day) in the case where a family doesn't have a radio or TV, or 170 Wh/day (13 Ah/day) in the case where it does. According to the manufacturer of the systems, the instructed electricity consumption is below the design value shown in Table 1, to let batteries recover after they have been discharged to a large extent.

2.4. Financial aspects

Since Sukatani is a pilot project, the financial situation with regard to SHS in Sukatani differs from a free-market situation. The SHS are owned by BPPT and used by the villagers. The user had to pay a down payment of 50,000 IDR. Furthermore, the monthly expenditure for an SHS in Sukatani is 4000 IDR/month[4]. This amount comprises collective savings for new batteries and the payment of the KUD, the Village Cooperative Unit, for the management of the PV project. In addition the user pays for the replacement of fused or defective strip lights. The use of SHS in Sukatani is cheaper than the use of energy equipment that people are applying when they do not have an SHS. In that case kerosine lamps are used for lighting and storage batteries to satisfy the remaining electricity demand. The 300 families that did not get an SHS are paying 13,000 IDR/month[5] for energy for lighting and electricity [27].

The SLS belong to BPPT. The villagers have to pay for the replacement of failing components.

2.5. Organization

One year after the introduction of the PV systems the management of the project in the village became the responsibility of the KUD. A chairman, a secretary and a technician attend to the operation and maintenance of the PV units, the collection of the monthly fees and the collective purchase of spare parts, like strip lights, lamp-inverters and batteries.

During the first five years of the project the KUD was supported by researchers from BPPT and PT R&S, the Indonesian subsidiary of R&S Renewable Energy Systems, who during their monthly visits assisted with the maintenance of the PV systems. At present the local technician visits each SHS during his monthly round through the village.

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[4] Rate of exchange: 1US$ = 1770 IRD (1989) [30].

[5] This value is given for 1987. We can compare this value to the average cash income of the villagers in 1988, namely 205,000 IDR/month, of which 140,000 IDR/month was used for food and 65,000 IDR/year for other needs [16].

3. Subjects for research

We consider two items of major interest for our research namely; (1) the service provided by the system; and (2) the interaction between the system and the user.

The service provided by the system is determined by

- the electricity production of the system, and
- the durability of the components.

We will investigate the service provided by comparing the measured electricity production in relation to the intended electricity production according to the system designer, and in relation to the available irradiation. In addition, the electricity production over the course of time will be analyzed. Furthermore, the durability of the components will be investigated by keeping an inventory of the failures and the time to failure of components and by observing degradation effects.

Both the electricity production of the system and the durability of the components are related to the size of the system and the quality of the components. In addition, the interaction between the system and the user influences the performance of the PV system. Therefore, we will investigate:

- the electricity consumed by the user
- the change in the electricity consumed over time,
- adaptations of the user's electricity needs to the available irradiation (on a daily and seasonal basis),
- changes in the set of appliances in time,
- other alterations to the original system configuration, and
- the users' opinions and experiences with the PV systems.

We will relate these issues to the instructions given to the users and to infrastructural items.

4. Measurements

Our investigations concentrate on an evaluation of data collected at a large number of SHS during field surveys, and monitoring data recorded by data loggers at a small number of PV systems. Below we describe the methods for the data collection, the kind of data and their availability.

4.1. Field surveys (1989–1997)

During a visit to Sukatani from 1–4 December 1997 we performed measurements on 62 SHS and interviewed the users of 22 of these 62 SHS. The

Table 2
Measured variables per channel of the data logger in the monitoring programme in Sukatani and daily cumulated variables

Channel	Variable	Half-hourly measurements Symbol	Unit	Sensor	Accuracy	Daily sums Symbol	Unit
1	Battery voltage	V_B	V	Resistance	± 0.1 V	n.a.	n.a.
2	Current from the array	I_A	A	Shunt	5%	$E_{I,A}$	Ah/day
3	Current to the load	I_{LOAD}	A	Shunt	5%	$E_{I,LOAD}$	Ah/day
4[a]	Irradiance in the array plane	$G_{i,ref}$	W/m^2	Reference cell RSM40	$\geq 5\%$ ± 15 W/m^2[b]	$H_{i,ref}$	kWh/m^2/day
	Temperature in the battery box	T_B	°C	–	2°C	n.a.	n.a.

[a] Channel 4 is either not used or is used for irradiance or temperature measurements.
[b] The accuracy of the reference cell is based on (1) a value of 3% $\pm$ 15 W/m^2 for a cell with temperature correction and without soiling [52], (2) the effect of not applying a temperature correction to the reference cells (1%), and (3) the effect of soiling (> 1%).

samples were taken randomly. The status of the 15 SLS was recorded in an interview with the village technician.

The measurement campaign of the SHS was to a large extent similar to the commissioning procedures of BPPT nowadays [31]. It comprised a visual inspection of the system and the appliances, and a series of measurements of the characteristics of the irradiance, battery, PV modules and BCR. The measurements on the BCR were done on 15 out of 62 systems. Appendix A lists the set of variables in the measurement campaign.

The purpose of the interviews was to assess the user's experience with the PV system. The questionnaire contained open questions about the user's opinion and knowledge about the usage and maintenance of the SHS. Furthermore, there were questions about the daily consumption pattern and the use of appliances in the long term. Appendix B contains the list of questions.

Furthermore, reports from previous field surveys were at our disposal, namely a technical field survey carried out by Pramusito in 1992 [12], an inventory of battery performance from 1988 to 1993 drawn up by Panggabean [21] and social and economic field surveys performed by Komarudin et al. [16] and Susmarkanto et al. [15].

4.2. Monitoring data (1988–1993)

For five years, from the start of the project in November 1988 to September 1993, the performance of eight PV systems, five SHS and three SLS, was monitored. Monitoring was executed with data loggers of the Squirrel type manufactured by Grant. This data logger has four measuring channels. Table 2 shows details of the variables that were measured and the measuring sensors. In all systems, the battery voltage, the current from the array and the current to the load were measured. In some cases the irradiance and the temperature in the

Table 3
Data of monitored PV systems in Sukatani that are used in this study

Name	Mama Mia	Mia	Ajuk	Hulaimi	Baihaki	Sudarman
Type	SHS	SLS	SHS	SHS	SHS	SHS
Monitored variables in addition to V_B, I_A and I_{LOAD}	T_B	$G_{i,ref}$	n.a.	n.a	n.a	n.a.
Availability of daily data: period	5/90–8/93	12/90–9/93	5/90–12/92	6/89–6/91	12/91	11/88–6/89
Availability of daily data: number of months in period	23	15	18	10	1	3
Availability of half-hourly data: period	10/90–3/92	9/90–7/92	n.a.	n.a.	n.a.	n.a.
Distance from the reference cell at SLS Mia (km)	0	0	2	3	2.5	2
TV	no	–	in 1992	yes	yes	yes
Radio/cassette	yes	–	yes	yes	yes	no
Date of first replacement battery	7/92	n.a.	10/92	3/93	n.a.	7/92
Capacity of new battery	100		70	70		100

battery box were measured as well. Voltage and current sensors were located in the BCR or TCU. The sample interval of the measurements was 18 s. Variables were stored as half-hourly averaged values. The current and irradiance figures were also stored as daily cumulated values.

Due to a number of causes the data set that is currently available for analysis is fairly incomplete. These causes are: sensor defects, breakdown of data loggers, unlogged interchange of data loggers between the eight systems, and inadequate long-term storage of the data.

For our evaluation, we use data for six PV systems. The availability and type of monitored variables and the distances between the systems are shown in Table 3. We can see from this table that periods with monitoring data do not overlap for all systems. Irradiance was measured at one site, namely SLS Mia. We use the irradiance data on a half-hourly basis to represent the irradiance at both SLS Mia and the neighbouring SHS Mama Mia and on a daily basis to represent the irradiation at the other five SHSs.

5. Results of field surveys of street lighting systems

In this section we describe the performance of the SLS at Sukatani using the field surveys from 1988 to 1997.

In 1993 all 15 SLS were operating [21]. In eight SLS the original batteries had been replaced by locally produced car batteries of 65 or 70 Ah.

In 1997 of the 15 initially installed SLS, 9 were working although all SLS had a broken TCU. One TCU had been replaced. The KUD asked BPPT to replace the other TCUs and indicated its willingness to pay. However, the local manufacturer could not supply the TCUs in such a small quantity. One of the nine working SLS does not light the street, but lights a nearby household.

Of the six remaining SLS, three had been converted to SHS and three were out of order; in one system the PV module was broken and in the other two systems the battery was broken. The broken parts had not been replaced, because of shortage of money at the KUD.

On the basis of interviews we found that in 1997 all the villagers in the sample ($n=22$) considered the SLS to be very useful and necessary in the village. There were even requests ($n=3$) for more street lighting systems in Sukatani. Some people, however, considered them to be too far away from the houses ($n=2$).

Although the SLS did not operate flawlessly, villagers appreciated them. We conclude that three factors affect the use of SLS in Sukatani:

1. the lack of infrastructure for the supply of spare parts, like the TCU,
2. the lack of financial support from the KUD in connection with the replacement of the batteries, and
3. the need for domestic lighting apart from outdoor lighting.

6. Results of field survey of solar home systems

Here we describe the performance of the SHS at Sukatani using the field surveys from 1988 to 1997.

The original set of 86 SHS has been extended with three SLS adapted for private use, so that there are now 89 SHS in the village. Since the start of the project 34% of the SHS have been moved to other households. Systems were moved if users were several months late with their monthly payment [32]. In 1997 two out of the 62 SHS visited were not operating due to broken batteries. The findings relating to the systems are summarized in Table 7.

6.1. The components

6.1.1. PV modules

In 1997, all PV arrays of the 62 SHS visited were in good order. This finding is based on single current and voltage measurements on the array. Our finding agrees with the general finding that PV generators rarely fail [1]. In 1992 it was found that 17 systems out of 86 were shaded [12]. The obstacles causing the shading, mainly trees, were subsequently removed. In 1997 we did not pay attention to shading.

6.1.2. Batteries

By 1997, 94% of the SHS had used up two batteries. From our interviews we learnt that if a battery breaks down the user has to wait several weeks for a replacement. Thus, we assume that sudden breakdown is the criterion for battery replacement.

Once a month the village technician measures the electrolyte density. We found no evidence that low values are used as a criterion for replacement. Uncertainties concerning the criteria for battery replacement, which also apply to European systems [33], play a role in the following results.

In the 62 systems inspected the initially installed batteries had an average lifetime of 50 months, see Fig. 1. Some batteries were used for 6 yrs. These lifetimes exceed the specifications of the manufacturer at 30°C and 10% *DDOD*,

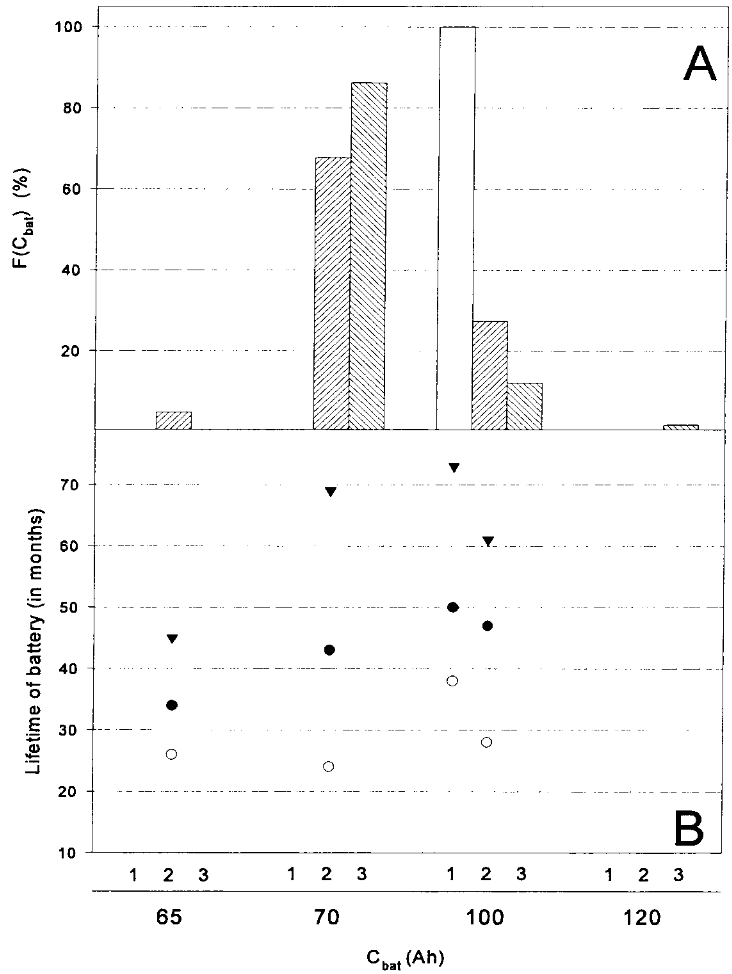

Fig. 1. (A) Frequency distribution of nominal capacities $C_{I,nom}$ of batteries in SHS in Sukatani as installed initially (white bar numbered 1), in the first replacement (dashed bar numbered 2) and in the second replacement (dashed bar numbered 3). (B) lifetime of batteries in Sukatani given per capacity and per batch, mean values (●), minima (○), maxima (▼). Lifetime is not given for the third battery, because this sequence is still in operation. Values based on the field survey in 1997 and Panggabean [21].

see section 2.1.2. The discrepancy is caused by the fact that the definition of the end of the lifetime of the batteries does not fit into the real circumstances in solar energy systems. The manufacturer gives the end of the lifetime at a rest capacity of 90% of the nominal capacity. In practice the batteries are used until they can no longer provide sufficient current, i.e. until their rest capacity is far below the nominal value. A capacity test by Brunia et al. on a 3.5 yr old Varta battery from Sukatani confirmed this [29]; the rest capacity was 68% of C_{nom}.

After the initial 100 Ah batteries for solar applications had broken down, they were replaced by locally produced automotive car batteries. The majority of these batteries of various brands had a capacity of 70 Ah, see Fig. 1. Also, batteries with a capacity of 65 Ah, 100 Ah and 120 Ah were installed. At present 86% of the SHS have 70 Ah batteries. This adaptation in the system design was recommended by BPPT in 1992 on the basis of investigations of the monitoring data for Sukatani [22]. They concluded that due to low electricity consumption the 100 Ah battery was not utilized fully and thus could be replaced by a smaller one. Of course at the same load a 70 Ah battery is discharged more strongly than a 100 Ah battery, which reduces the lifetime of the battery. Fig. 1 shows that on average 70 Ah batteries last 7 months less than 100 Ah batteries. However, on the assumption that a 70 Ah battery costs 30% less than a 100 Ah battery[6], it can be concluded that the 70 Ah batteries save about 20% of the lifetime costs compared to 100 Ah batteries.

In Fig. 1 we see that locally produced automotive car batteries with a capacity of 100 Ah last 3 months less than the initially installed batteries which are designed for solar applications and which have the same capacity.

The average lifetime of 70 Ah batteries depends on the brand and is 38–48 months. The average lifetime of 65 Ah batteries is 34 months.

In 1997 the electrolyte density of the batteries was measured using a hydrometer. Differences in the electrolyte densities in the cells of one battery indicate that a battery can break down in the short term[7]. In three out of 62 systems we found electrolyte densities differing by more than 0.02 g/cm^3. Also, in three out of 62 systems we found broken cells in the battery. An electrolyte density below 1.15 g/cm^3 signals a worn-out battery which may fail in the short term. We observed too low densities in 11% of the SHS inspected.

We conclude that the majority of the currently installed batteries function well.

6.1.3. Battery charge regulator

In 1997, we found one broken BCR. Eleven out of 62 BCRs had already been replaced.

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[6] In 1997 the average selling price for a single battery in Indonesia was 1000 IRD/Ah. However, because of a discount on bulk purchases a number of batteries sold together could have cost less per ampère-hour than single batteries.

[7] If the difference between the cells was less than 0.02 g/cm^3 the batteries could be improved by an equalization process.

Table 4
Specified set points and measured set points of 15 initially installed battery charge regulators in the Sukatani project. The accuracy of the measurements is 0.1 V

Set point	Specified value (V)	Measured average of sample (V)	Minimum measured in sample (V)	Maximum measured in sample (V)
Overcharge-protection voltage	14.2	14.2	13.3	14.8
Charge-reconnect voltage	13.6	13.5	12.4	14.0
Discharge-reconnect voltage	12.2	12.1	11.7	12.6
Deep-discharge-protection voltage	11.6	11.3	11.0	11.8

We measured the set points of 15 initially installed BCRs with an accuracy of 0.1 V. The results are presented in Table 4. The average values of the set points are within 0.3 V of the specified values, but individual values can deviate by up to 1.2 V. These deviations can not be explained by a degradation of the electronic components in the BCR. According to the manufacturer this may result in an alteration of a setpoint of about 0.1–0.2 V. A case of special concern is the occurrence of a deep-discharge-protection voltage of 11.0 V in five systems. Measurements of discharge curves at I_{100} of Indonesian car batteries performed by Kuhmann et al. showed that at this voltage level the battery SOC is negative (!) [34]. Thus, the BCRs in Sukatani do not always prevent very deep cycling of the batteries, which can reduce the lifetime of a battery [35].

Another case for concern is the occurrence of an overcharge-protection voltage which exceeds the specified value of 14.2 V in seven systems. Excessive overcharging leads to extensive corrosion of the positive grid and, hence, to accelarated ageing of a battery [35].

In many cases (22%) villagers by-passed the BCR by connecting the battery straight to the load. In one household the array was directly coupled to the battery because the terminals of the BCR were broken.

6.2. The load

6.2.1. Installed applicances

Back in 1992 [12] it was observed that people in the village were making incandescent lights with low power between 1–5 W. We will call them small bulbs, SBs. Usually they consist of a small fairy light inside a worn-out bulb where the socket has been removed. The luminous efficacy of fairy lights is low compared with strip lights [36]. The reason for using them is their low price, namely 600 IDR[8] (for comparison: a strip light costs 13,000 IDR). Furthermore, Indonesian people prefer to sleep with the light on. Hence, SBs are often installed in the bedroom.

[8] Rate of exchange at the end of 1997: 1$ = 2.600 IRD (author's note)

We observed a strong increase in the number of SBs in the course of time, see Fig. 2. In 60% of the households various numbers of SBs are used. They count up to eight. In the meantime, the number of installed strip lights decreased, see Fig. 2. In 1997, 66% of the households had two or less strip lights. Media devices such as radio and TV are widespread. Fig. 2 shows the growth in the number of these devices from before the start of the project until 1997.

Intercoms became rather popular in Sukatani after the installation of the SHS. In 1989, 26% of the household used such a device for personal communication and for outdoor broadcasts of religious gatherings in the mosque [37]. In 1997, we did not count the intercoms.

6.2.2. *Wiring*

In 1992 it was noticed that 56% of the villagers used extra wiring in their SHS although this was prohibited according to the instruction sheet [10]. In 51% of the cases they used extra wiring in order to add appliances and in 5% of the cases in

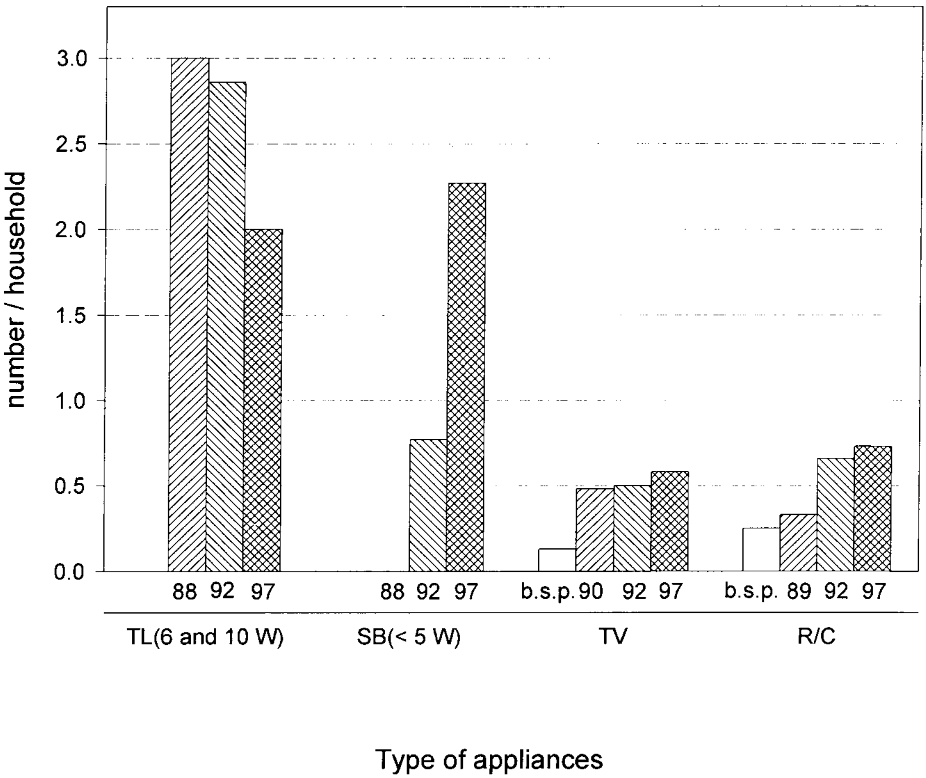

Fig. 2. Installed appliances per household in Sukatani before the start of the project (b.s.p.), at the start of the project in 1988, and during the project in 1989, in 1990, in 1992 and in 1997. TL, strip light; SB, small bulb; TV, television; R/C, radios and cassette players. Sources: Komarudin et al. [37], Panggala [10], Pramusito [12] and the field research in 1997.

order to provide electricity to a second household. In 1997 we did not see the latter phenomenon.

Still there is a need to distribute electricity over more rooms and appliances than in the initial situation in 1988. Thus, the wiring network has been extended in 61% of the households (with respect to the initial situation in 1988). In 43% of these cases the extension had been executed in an amateurish manner which could cause the system to fail.

6.2.3. Load according to the user

To determine the average daily electricity consumption in 1997, we asked users to fill in a time schedule for their hourly use of appliances on an average day. A frequency distribution of the daily consumption based on these time schedules is shown in Table 5. The mean value is 225 Wh/day. This is an increase of 45% with respect to the consumption in 1992, which was 155 Wh/day [12]. The mean value in 1997 corresponds to the design value for electricity consumption as shown in Table 1. We should interpret the result of these interviews with some caution, because users may have overestimated their consumption. On the other hand, there are several mechanisms for extracting more energy from the system, namely (1) by-passing the battery (shown in Fig. 4), (2) the prolonged use of small power appliances and (3) demand-side management, and (4) a low value for the specified deep-charge-protection voltage of the BCR (see section 6.1). Obviously, a daily consumption of 390 Wh as shown in the figure can occur occasionally, but not each day. We found no correlation between the daily electricity consumption as reported by the villagers and the battery lifetime of the batteries, the battery capacity and the by-passing batteries.

Table 5
Frequency distribution in classes of 50 Wh/day of daily electricity consumption as determined from interviews with 22 users of SHS in a field survey in Sukatani in 1997 and daily electricity consumption of 44 users in 1992 [12]. Included are batteries by-passed in 1997

Classes of daily electricity consumption (Wh/day)	1992 (44 users) (%)	1997 (22 users) (%)	By-passed batteries in 1997 sample (%)
0–50	0	0	0
50–100	23	0	0
100–150	32	18	0
150–200	23	18	14
200–250	9	36	14
250–300	11	5	5
300–350	2	18	5
350–400	0	5	0
Total	100	100	38
Average daily electricity consumption	155 Wh/day	255 Wh/day	

The daily load pattern of the largest and the smallest consumer as well as the average value of the sample are shown in Fig. 3. We found that the bulk of electricity is consumed in the evening by the television and the lighting. The load in the morning is mainly due to use of a radio or a cassette recorder. Strip lights are used in the period between dusk and sunrise and they burn in the evening till people go to bed. SBs are used during the evening and night.

Furthermore, according to the 22 villagers interviewed on average 2 out of the 3 installed strip lights are used in combination with a single SB. Although 72% of the interviewed villagers had more than one SB installed, they said that in fact only one SB was used. Furthermore, although 64% of the users interviewed had installed more than three lights (TL as well as SB), 91% said that they used less than three lights. Both findings may be explained by the fact that BPPT dissuades people from using self-made low power lights and that the use of more than three lights is prohibited according to the instruction sheet [10].

In Table 6 we show the average hours/day that each appliance is used according to the villagers. It can be seen that the third strip light is hardly used due to the fact that not every user in the sample has three strip lights.

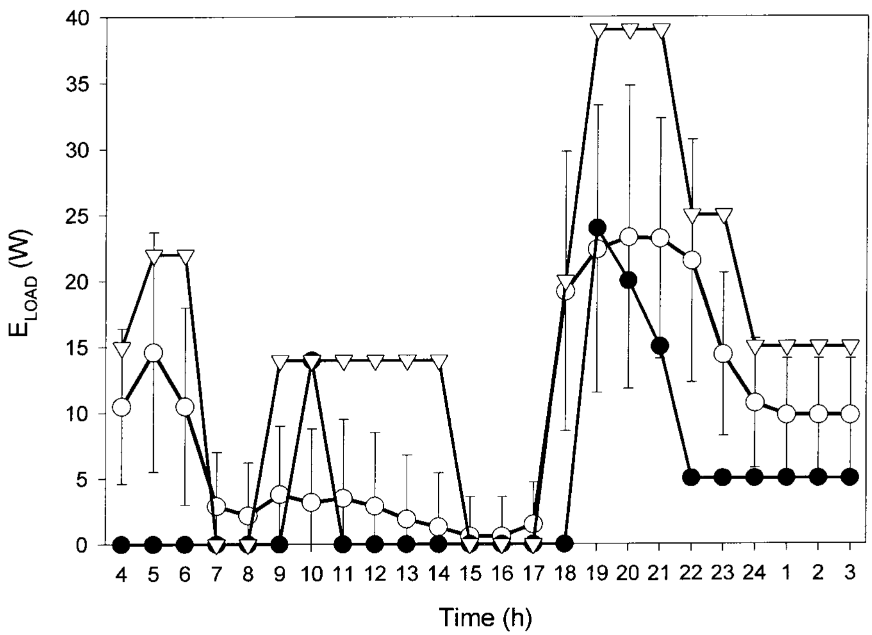

Fig. 3. Daily load patterns as determined from interviews with 22 users of SHS in a field survey in Sukatani in 1997: average value with standard deviation (○), largest consumer (▽) and smallest consumer (●).

Table 6
Use of appliances in hours per day as determined from interviews with 22 users of SHS in a field survey in Sukatani in 1997. Minimum and maximum use is given if the appliance considered was mentioned by the person interviewed

Appliance	Average use (h/day)	Minimum use (h/day)	Maximum use (h/day)
Strip light Number 1	6	3	13
Strip light Number 2	6	1	13
Strip light Number 3	0.8	5	8
Small bulb Number 1	10.8	7	13
Small bulb Number 2 and more	0	0	0
Radio and cassette	3.2	2	11
Television	2.4	2	9

6.3. The user's opinion

Most of the 22 people interviewed appeared to be pleased with the SHS in the village. They declared that SHS are good for many purposes: lighting the house ($n=11$), children's study ($n=10$), saving on the cost of kerosine ($n=3$), working in the evening ($n=2$), reading ($n=2$), independence ($n=1$), kerosine lamps are no longer needed ($n=1$), and they operate the radio ($n=1$). They didn't mention the possibility of watching TV.

About half of the people interviewed were unreservedly positive about the SHS. The other half reacted with conditional approval, mentioning the need for battery replacement ($n=13$) and the long wait for a new battery ($n=3$).

The users admitted that they alter their electricity consumption during the rainy season. This was not mentioned as a disadvantage of the SHS.

The battery is maintained either by the technician ($n=15$) or by the user ($n=7$). We were told that some people use rain water for topping up the electrolyte liquid, but no one admitted that he or she did this.

Furthermore, the purpose of the indicator light at the BCR is understood by all users except one.

6.4. What if the electricity grid comes to the village?

To the question 'Which is better: electricity from the grid or from an SHS' we mainly got positive reactions ($n=22$) regarding the SHS. The answers were: 'there is no grid yet' ($n=16$), 'SHS-electricity is cheaper than electricity from the grid' ($n=4$) and 'an SHS is safe' ($n=3$). Other answers were: 'both are useful' ($n=2$), 'the grid is better, but more expensive' ($n=1$), 'the grid is not reliable in the rainy season' ($n=1$), and 'an iron or water pump can be used via the grid' ($n=1$). Reasons for the positive view of SHS can vary from collective positive thinking (don't forget that Sukatani is a model village) and being satisfied with the things that are available

Table 7
Results of the 1997 technical field survey of the SHS in Sukatani

Item	Number of systems which have been inspected	Number of systems where the item has been observed	Percentage of systems where the item has been observed (%)
Change of ownership	86	29	34
System does not function (due to broken battery)	62	2	3
Unauthorized change of cables	54	33	61
Bad condition of cables	54	14	26
Battery not in box	62	16	26
By-pass between battery and load	62	14	23
Direct coupling between array and battery	62	1	1–2
Two battery replacements	62	57	92
Households currently have a 70 Ah battery instead of a 100 Ah battery	62	53	85
Broken cell in the battery	62	3	5
Different electrolyte density in the cells of the battery	62	3	5
Too low electrolyte density (<1.15 g/cm^3) in the battery	62	7	11
Broken BCR	62	1	2
Replaced BCR	62	11	18
Presence of incandescent lights of 5 W or less	60	35	60
Presence of fluorescent lights	60	58	97
Presence of a TV	60	35	60
Presence of a radio	60	41	68
Installation of a grid connection box	60	26	43
Availability of electricity from the grid	60	1	1–2

(the SHS), to being really satisfied with the PV systems. Our interviews did not contain sufficient information to discriminate between these reasons.

One month before our field survey took place, an unknown contractor installed connection boxes and cabling for the electricity grid in the houses. This means that the conventional grid may come to the village in the near future. Forty-three percent of the households with an SHS let a grid connection box be installed and thus demonstrated their interest in obtaining a connection to the grid.

Six people with a connection box who were interviewed mentioned as their reason for allowing the box to be installed that they would like to use powerful devices, like an iron, colour TV and machines in their business (football manufacturing, wood crafting).

Electricity from the grid is currently available in one household at the edge of the village. It is supplied by an unauthorized cable from a neighbouring village. This household still has an SHS, but keeps it for the frequent moments when the grid fails.

7. Results of the monitoring data

In this section we analyse the data that were monitored in the period 1989–1993. First, we discuss the irradiation (section 7.1) and the energy performance of the PV systems over short and long time-spans (section 7.2). We also investigate the relation between the user's electricity consumption and the available irradiance (section 7.3). Next, we perform an energy loss analysis of the PV systems (section 7.4). Finally, we investigate the design of the SHS (section 7.5).

7.1. Irradiation in Sukatani

In an analysis of the monitoring data recorded at Sukatani in 1989 and 1990 Panggala [10] found an in-plane irradiation of 4.2 kWh/m^2.day. This value is 20% higher than the estimated value used for the design calculations (3.5 kWh/m^2/day). When we compare this value to long-term data for the few other locations in Indonesia for which we have data [38], we find that the value at Sukatani is equal to the value for Medan on Sumatra, and Samarinda on Kalimantan. It is 25% lower than the value for the location with highest irradiation, namely Waingapu on the island of Sumba. Data in Medan and Samarinda were obtained with pyranometers; these yield higher values than measurements with reference cells. Furthermore, it is possible that in the hot season measurements in Sukatani underestimate the irradiation because of soiling of the reference cells with dust. Hence, we conclude that the irradiation in Sukatani is equal to or slightly better than the average irradiation in Indonesia.

On a monthly basis, the irradiation at Sukatani is more stable than at other

locations; in Sukatani the maximum monthly deviation from the annual average is 10% whereas in Samarinda the deviation is 25%, see Fig. 4.

The daily irradiation profile depends on the season. In Fig. 5 we present an average daily irradiance profile for January and February 1992 (the middle of the rainy season) and for September and October 1991 (the end of the hot season). The average irradiation is higher in the hot season than in the rainy season. However, we found that the maximum daily irradiation is higher in the rainy season than in the hot season, namely 6.8 kWh/m^2/day versus 5.4 kWh/m^2/day. Also the maximum half-hourly irradiance is higher in the rainy season than in the hot season, namely 955 W/m^2 vs 885 W/m^2. These findings can be explained by the seasonal dependence of the sky. In the hot season there are no clouds, but the atmosphere is hazy and the open air may contain a lot of dust due to the absence of rain. In the middle of the rainy season, it rains for a few hours almost every day. But, in between the showers and the clouds the sun can may shine brightly due to very clear sky conditions.

If the difference between the maximum half-hourly irradiance in the rainy season and the hot season is caused by the difference between irradiance measurements with a clean reference cell and irradiance measurements with a reference cell which is covered with dust, the seasonal effect of reduced transmission of irradiance due to contamination of the reference cells may be in the order of 10%.

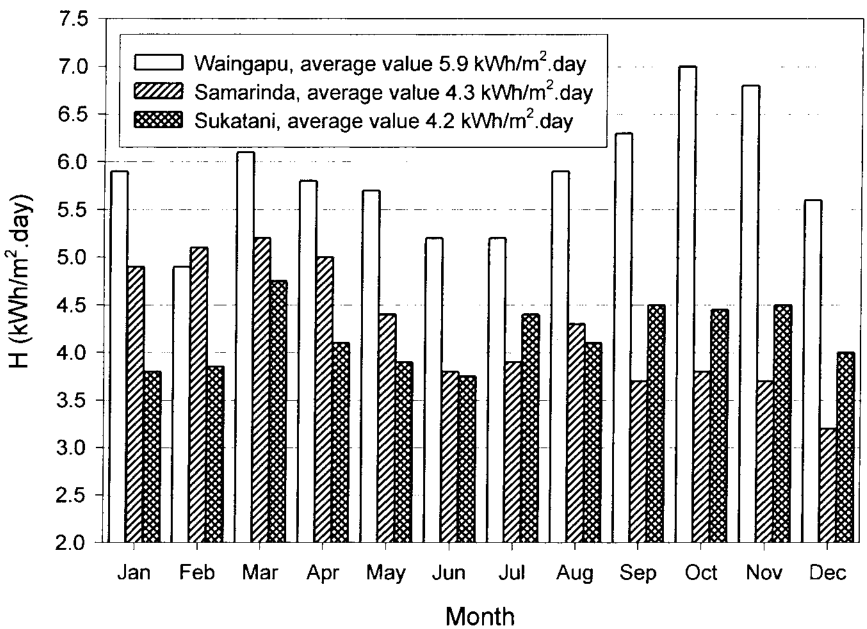

Fig. 4. Mean daily irradiation per month in Sukatani measured with a reference cell at 10° tilt angle and averaged over 2 years by Panggala [10], and mean daily irradiation per month in Samarinda and Waingapu measured by Rosyid [38] with a pyranometer in the horizontal plane averaged over 5 and 4 year respectively.

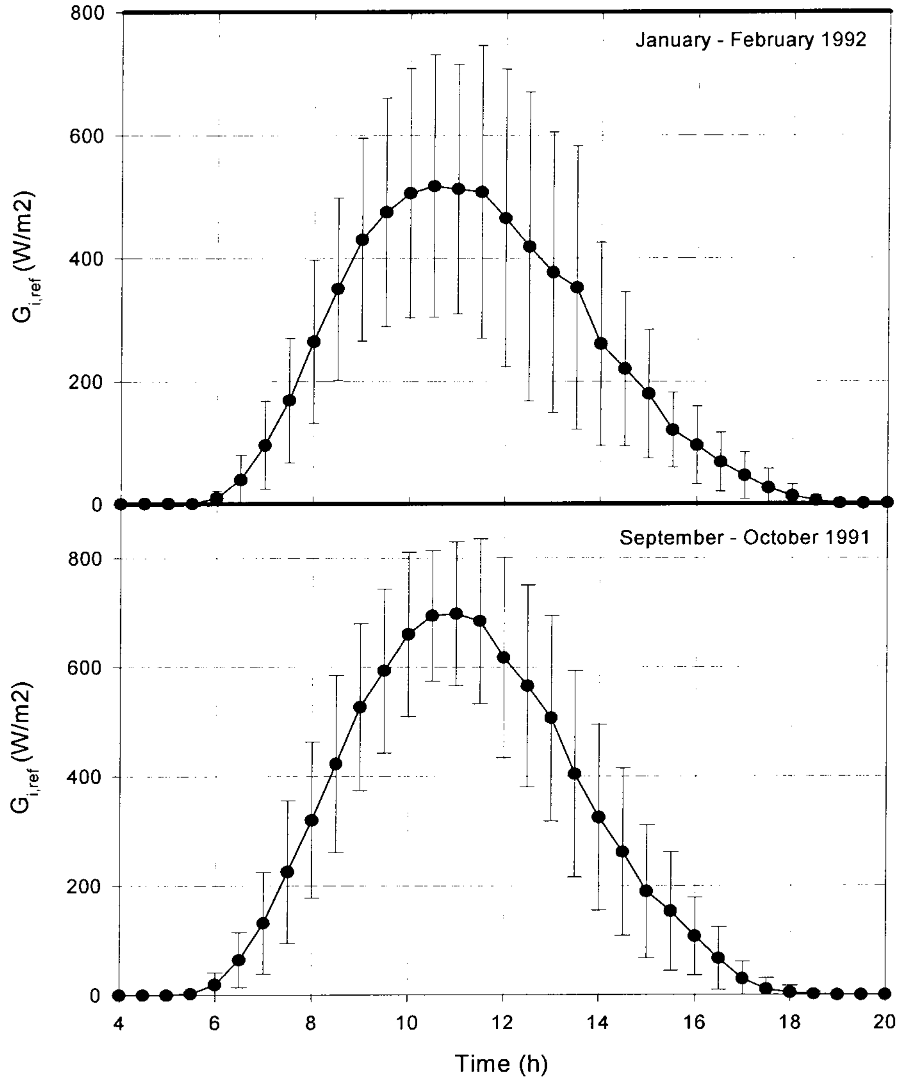

Fig. 5. Average daily irradiance profile in Sukatani and the standard deviation measured with a reference cell at 10° tilt in Sukatani in January and February 1992 (wet season) and in September and October 1991 (hot season). Mean irradiation in these periods is 3.5 kWh/m^2/day and 4.1 kWh/m^2/day respectively.

7.2. The energy performance of the PV systems

We investigate the performance of the SHS and an SLS on the basis of monitoring data recorded during the first five years of the project. In order to

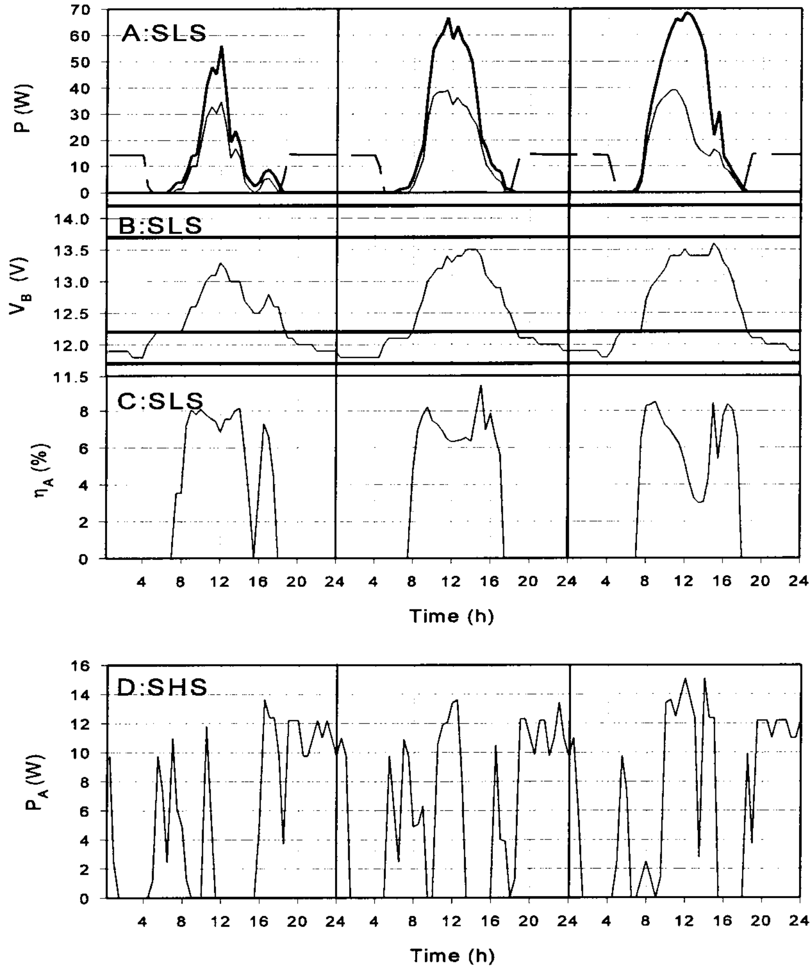

Fig. 6. Time series of monitoring variables from SLS Mia on 25, 26 and 27 October 1991. (A) the available power from the PV array at STC efficiency based on irradiance: thick solid line; actual power from the array: thin solid line; power to the load: dashed line. (B) the battery voltage: thin line, and the specified set points of the BCR: thick lines, and (C) the array efficiency. (D) Power to the load in SHS Mama Mia in the same period.

restrict uncertainties in the evaluation we mainly use directly recorded data as are shown in Table 2. As a consequence the energy performance and indicators of the PV systems are presented and calculated into units of current, i.e. Ah[9].

[9] Ampère-hours, Ah, can be translated into units of energy, i.e. kilowatt-hours, kWh, by multiplying it by a conversion factor. The factor is found by an investigation of half-hourly monitoring data of 3PV systems. A conversion factor of 13.5 Volt ($V_{TB/mean}$) can be used to obtain the electricity from the array and 12.5 Volt ($V_{FB/mean}$) to calculate the electricity to the load. In this factor a voltage drop of 0.6 V over the diode in the controller is taken into account.

Here, we diverge from the guidelines for the monitoring and analysis of PV systems as published by the JRC [39] and the IEC [40]. These guidelines recommend the measurement of power instead of current.

7.2.1. An example of the short-term performance

As an example of the performance of PV systems in the field we show in Fig. 6 the time series of variables taken from SLS Mia on three successive days. The irradiation increases from very low to very high values, namely from 2.5, via 4.4 to 5.3 kWh/m^2/day.

In Fig. 6A we can see that the load of the SLS is switched on from sunset to about 4 am. So all energy goes through the battery. The first day, the battery voltage does not reach the maximum, see Fig. 6B. All power produced by the PV array is fed into the battery at an average array efficiency of 8.1%[10], see Fig. 6C. The efficiency of the PV array is lower than the STC efficiency of 11.1% because (1) the module temperature is above 25°C, (2) there are ohmic losses in the cables and (3) the PV array operates below the maximum power point.

The next day irradiation is higher and the battery voltage reaches a plateau at about 2 am. This is due to the overcharge-protection voltage of the BCR. The half-hourly value of the voltage on the plateau is below the specified value of the overcharge-protection voltage and the recharge-reconnect voltage. This is due to the regulation of the current from the PV array to the battery, and due to the lowering of the setpoints resulting from the compensation of the battery temperature by the BCR. Because of the regulation of the current from the PV array on this day the average array efficiency of 6.4% is lower than on the first day.

On the third day additional regulation of energy further reduces the array efficiency to 5.5%. The half-hourly array efficiency at the end of this day increases because the battery voltage falls below the overcharge-protection voltage at low irradiance and regulation of energy therefore stops.

Fig. 6D presents the electricity consumption pattern of SHS Mama Mia in the same period as the SLS Mia. The pattern is irregular with peaks in the morning, at noon and in the evening. We found that in this system the daily maximum of battery voltage is usually reached between 10:30 h and 16:00 h.

The temperature in the battery box[11] of SHS Mia during these three days is 24 $\pm$ 1°C with a minimum value of 21.6°C at night and a maximum value of 26°C during the day. Such a slight daily variation of temperature occurs throughout the year and is characteristic of the tropical climate in Indonesia [38]. Hence, a

[10] The array efficiency is based on the cell area of the PV modules

[11] We do not have information at our disposal on the exact location of the temperature sensor. This information is important for the interpretation of our finding. For instance, if the temperaure sensor is located below the battery and if the battery is placed on the floor of the house, temperature measurements will have small variations due to the large heat capacity of the floor. The variation of temperature will increase if the sensor is installed at the top of or inside the battery.

correction of the battery voltage for temperature effects in the battery is not required in the BCR.

7.2.2. Long-term monthly performance of the PV systems

In order to assess the long-term performance of the monitored SHS ($n = 5$) and the SLS, we present in Fig. 7 monthly values of irradiance and the electricity production of these six PV systems during the first 5 yrs of the project. Information about these systems and the data available can be found in section 4.2.

First, we observe in Fig. 7 that irradiation decreases by 4% a year. This effect may be caused by soiling or shading of the reference cell, but another possibility is reduced data availability in the period 1991–1993. In our further analysis we do not correct for this phenomenon. The mean value of irradiation in this period is

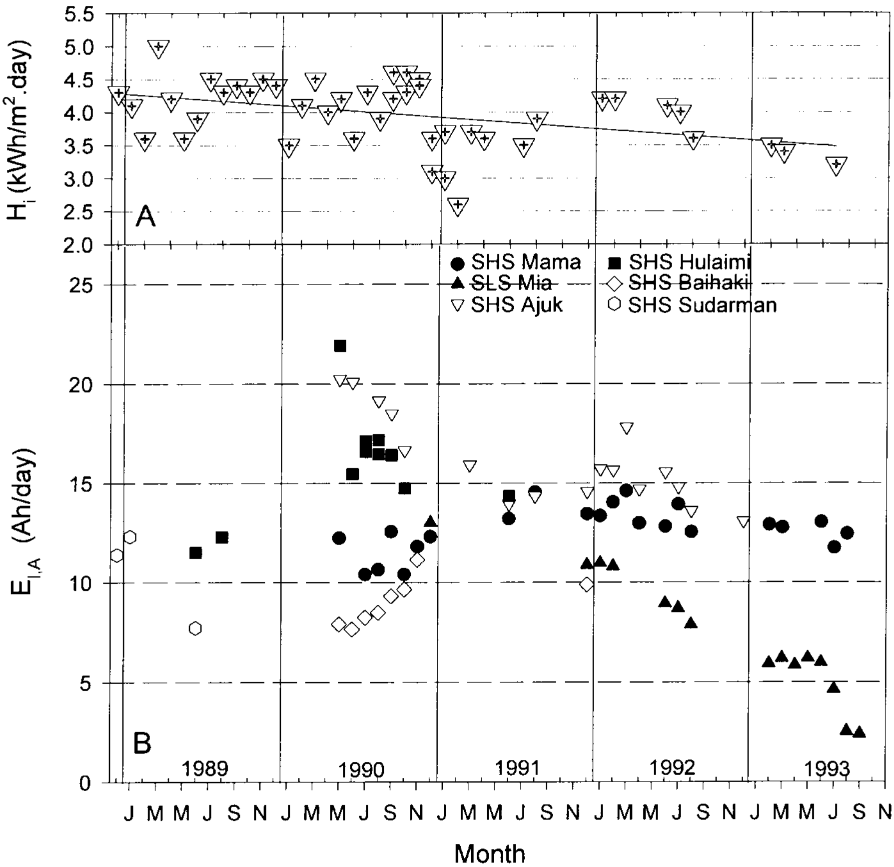

Fig. 7. (A) Monthly irradiation (triangles with cross) and a first order regression (solid line). (B) monthly electricity produced by the array of 6 PV systems in Sukatani. Sources: monitoring data presented in Table 3, Panggala [10] and Pramusito [53].

3.9 kWh/m^2/day. The average daily electricity production by the PV arrays of the five SHS is between 9.1–16.1 Ah/day, see Table 8. Further, per system the average daily electricity production by the PV array varies from month to month up to 30%.

By observing Fig. 7, we found no relation between the monthly variation in the electricity production and the seasonal dependence of irradiation. Hence, the variation results from changes in consumer patterns or defects of components and degradation of batteries in the SHS. Unfortunately, we have no information on these three aspects in the period considered. In the case of SLS Mia the electricity production gradually decreases due to an unknown defect.

Table 8 shows the values for the energy flows in the six monitored systems. We can see that the mean electricity consumption is far below the design value of 17.3 Ah/day. Deviations vary from −50% (SHS Baihaki consuming 8.8 Ah/day) to −14% (SHS Ajuk consuming 14.8 Ah/day) with respect to the design value. On the other hand, these values are close to those in the instructions given to the users, namely 10 Ah/day for a household without television and 13 Ah/day for a user with television. However, no correlation is found between the presence of a TV set, see Table 3, and the measured electricity consumption. For instance, Baihaki has a TV, but this household consumed 10% less electricity than the

Table 8
Irradiation, energy, Coulomb efficiency, daily depth of discharge and performance ratio and *UE* for 6 PV systems in Sukatani. In each case the larger number of months evaluated comprises the smaller number below

System	Number of months evaluated	$H_{i,ref}$ (kWh/m^2/day)	$E_{I,A}$[a] (Ah/day)	$E_{I,LOAD}$[b] (Ah/day)	$\eta_{I,B}$[c] (%)	DDOD[d] (%)	PR_I[c] (%)
SHS Mama Mia	22	–	12.7	11.3	89	12	–
	16	4.0	–	11.1	–	–	47
SLS Mia	15[e]	–	7.4	6.2	84	3.3	–
	3[f]	4.0	11.6	10.7	92	5.7	45
SHS Ajuk	17	–	16.1	14.2	88	15.3	–
	12	4.1	–	14.8	–	–	62
SHS Hulaimi	9	–	15.6	14.2	91	15.3	–
	8	4.2	–	14.3	–	–	58
SHS Baihaki	8	–	9.1	8.8	97	9.5	–
	7	4.2	–	9.2	–	–	36
SHS Sudarman	3	4.1	10.5	9.8	94	10.5	40

[a] The electricity production in Wh/day can be estimated by multiplying the values in this column by $V_{TB,mean} = 13.5$ V.
[b] The electricity consumption in Wh/day can be estimated by multiplying the values in this column by $V_{FB,mean} = 12.5$ V.
[c] This indicator can be converted to a value based on power by multiplying the values in this column by $V_{TB,mean}/V_{FB,mean} = 0.926$.
[d] Based on $C_{I,nom} = 93$ Ah.
[e] A gradual defect yield lower values for $E_{I,A}$ and $E_{I,LOAD}$.
[f] Here, we consider the months in which the system is not affected by the gradual defect.

minimum recommended. And the biggest user, Ajuk, did not have a television until 1992 and consumed 14% more than the maximum consumption recommended.

In Table 8 we also present the mean battery efficiency on a current basis, the Coulomb efficiency, $\eta_{I,B}$ (%). It is defined by:

$$\eta_{I,B} = \frac{E_{I,LOAD}}{E_{IA}} \tag{1}$$

where, $E_{I,LOAD}$ is the daily current to the load (Ah/day), and $E_{I,A}$ is the daily current from the array (Ah/day).

We can see that for SHS under normal operation $\eta_{I,B}$ ranges from 88% to 97%, with an average value of 92%. The low value of 84% in the case of SLS Mia is caused by the defect mentioned.

In order to investigate the depth of cycling of the batteries, we calculate the average depth-of-discharge, $DDOD$ (%), by

$$DDOD = \frac{E_{I,LOAD}}{C_{I,nom}} \tag{2}$$

where, $E_{I,LOAD}$ is the daily current to the load (Ah/day), and $C_{I,nom}$ is the nominal battery capacity at I_{100} (Ah).

In Table 8 we present the values of this indicator based on the real nominal capacity of the batteries in Sukatani $C_{I,nom} = 93$ Ah (see section 2.1). The mean value of the $DDOD$ is 12.7% for the SHS and 5.7% for the SLS with a double battery capacity with respect to the SHS. Hence, the batteries initially installed in Sukatani are discharged to a limited extent.

In order to assess the use of energy produced by the SHS, we calculate the performance ratio on a current basis, PR_I (%), in Table 8 is defined by:

$$PR_I = \frac{E_{I,LOAD}\ V_{TB,mean}}{H_{i,ref}\eta_{STC}A_{PV}} \tag{3}$$

where, $E_{I,LOAD}$ is the daily current to the load (Ah/day), $H_{i,ref}$ is the daily irradiation (Wh/m^2/day), η_{STC} is the efficiency of the PV modules at STC (11.1%), A_{PV} is the cell area of the PV array (0.72 m^2), and $V_{TB,mean}$ is the mean value of charge voltage (13.5 V).

The mean value of the PR_I for each system is calculated for all months in which both irradiation and electricity to the load are available.

In Table 8 we can see that PR_I for SHS ranges from 36% to 62%, with an average value of 49%. Fig. 8 presents monthly values of PR_I for the six PV systems, together with the design value, $PR_{I,design}$, which is based on the measured irradiation and the design load given in Table 1. For SHS and SLS, the value of $PR_{I,design}$ is 70% and 58% respectively, (based on $H_{i,ref} = 4.2$ kWh/m^2/day and $E_{I,LOAD} = 17.3$ Ah/day and 14.4 Ah/day respectively). Although monthly values of PR_I sometimes exceed $PR_{I,design}$, average values are far below the design value. As

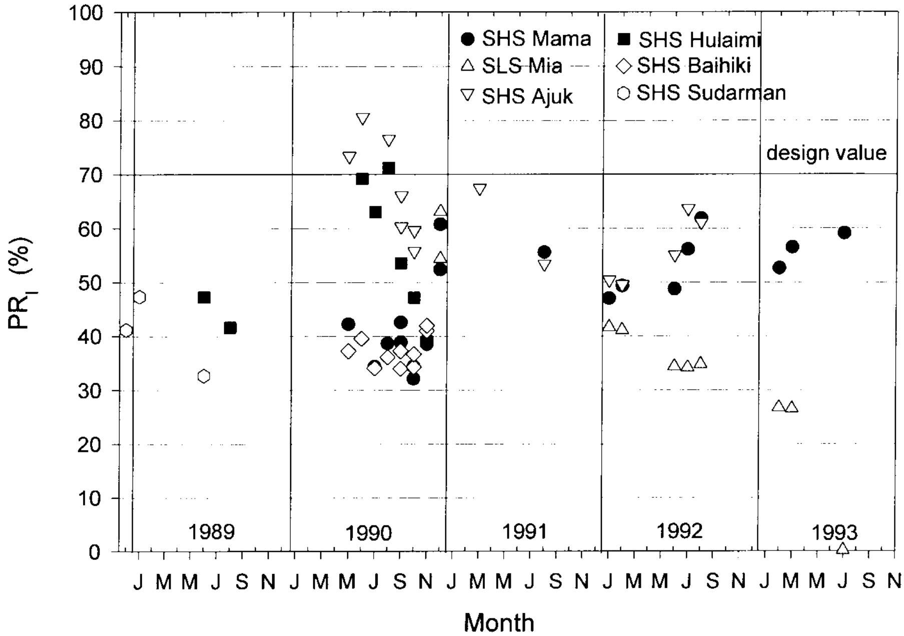

Fig. 8. Monthly PR_I of 6 PV systems in Sukatani. Sources: monitoring data taken from Table 3, Panggala [10] and Pramusito [53].

a consequence the PV systems in Sukatani operate at low efficiency. In the case of SHS Baihiki, the system efficiency is 3.7%. In the case of SHS Ajuk, due to higher consumption, the system efficiency is 6.3%.

Hence, part of the energy that could be generated on the basis of available irradiation is not used.

We can calculate the unused energy, *UE*, as a percentage of the available energy from:

$$UE = (PR_{\mathrm{I,design}} - PR_{\mathrm{I,measured}})\frac{V_{\mathrm{FB,mean}}}{V_{\mathrm{TB,mean}}} \tag{4}$$

where, $PR_{\mathrm{I,design}}$ is the design value of the performance ratio (%), $PR_{I,measured}$ is the measured performance ratio (%), $V_{\mathrm{TB,mean}}$ is the mean charge voltage (13.5 V), and $V_{\mathrm{FB,mean}}$ is the mean discharge voltage (12.5 V).

Values for *UE* are given in Fig. 9. We see that 10–34% of the expected energy is not used. Furthermore, we observe a linear relationship between electricity consumption and *UE*, which supports the idea that low consumption levels restrict the amount of energy produced by the system. The regression line cuts the *x*-axis at a value of 17.3 Ah/day and the *y*-axis at a value of 70%. These values are equal to the design values of the daily load and the performance ratio, respectively.

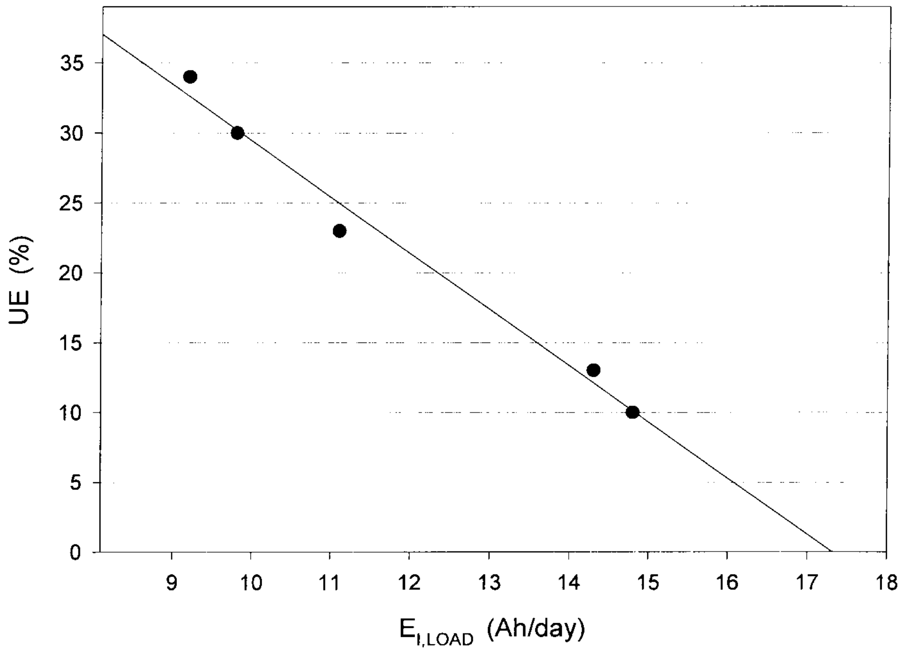

Fig. 9. Long-term average electricity consumption, $E_{\mathrm{I,LOAD}}$, and unused energy, *UE*, and a first order regression (solid line) for five SHS in Sukatani.

7.3. The relation between daily electricity consumption and irradiation

In order to investigate the relation between the users' daily electricity consumption and the weather, i.e. the amount of irradiation, we distinguish between two cases, namely the case of an SLS in which the electricity need is known to be independent on the weather, and the case of an SHS which we want to investigate. For three SHS, we also study the daily electricity consumption as a function of time.

7.3.1. The relation between daily consumption and irradiation

For the period July–August 1992 we made plots of the daily electricity consumption vs irradiation for both an SHS (Ajuk) and an SLS (Mia), see Fig. 10. In the case of fixed consumption, the SLS, we notice that the daily electricity production is limited by the consumption at night. This leads to a constant daily electricity production and partial use of the available energy from the irradiance.

In the case of the SHS, we see that above an irradiation of 2 kWh/m^2/day the consumption by the SHS user is not related to the irradiation and that below this value the electricity production is linearly related to the irradiation. This means that the battery can always be recharged. A similar result is found for SHS Mia.

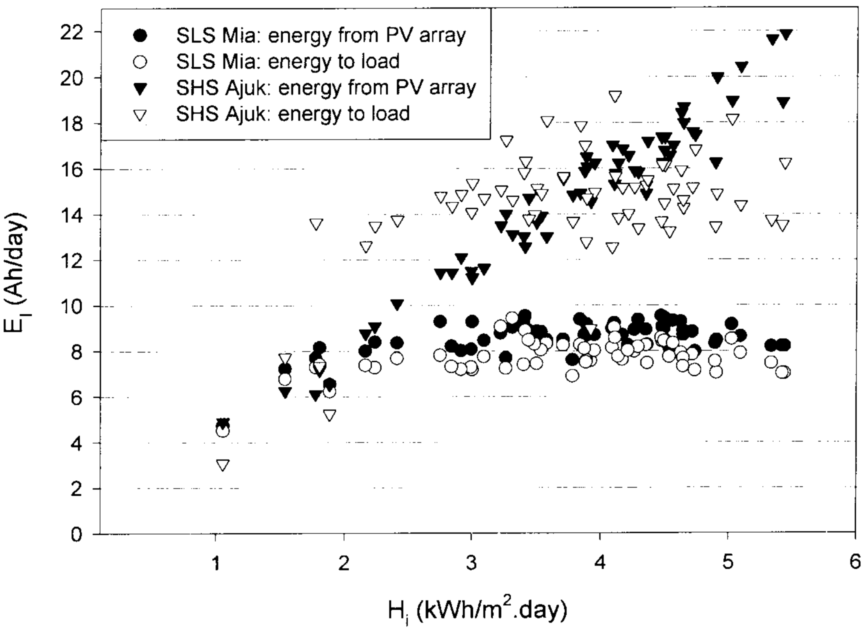

Fig. 10. Daily irradiation and electricity production and consumption for SLS Mia, and for SHS Ajuk, Period: July–August 1992.

7.3.2. The daily consumption as function of time

In order to investigate the daily electricity consumption in the long term and to investigate its dependency on the season, we plotted in Fig. 11 a time series of daily values of the electricity consumption for three SHS in various periods from 1989–1993. In each case the daily consumption varies from 0 to 25 Ah. We can not observe a seasonal dependency of the daily electricity consumption. The average load in the long term is rather constant for SHS Mia and SHS Ajuk. In SHS Hulaimi, the load grew in one year by 50% with respect to the start in 1989 and then decreased gradually. The monitoring data do not give the information needed to explain the changes in the daily electricity consumption.

7.4. Energy loss analysis of PV systems

In order to evaluate the overall performance of the PV systems in Sukatani we calculate the energy losses that occur in SLS Mia and in the neighbouring SHS Mama Mia. The energy losses are calculated on the basis of half-hourly monitoring data recorded in the period March 1991–February 1992 for SLS Mia and in the period August 1991–November 1991 for SHS Mama Mia. In these periods irradiance yielded 3.6 and 3.7 kWh/m^2/day respectively. Calculations are performed in the simulation system INSEL version 4.80 [41] and include the following energy losses.

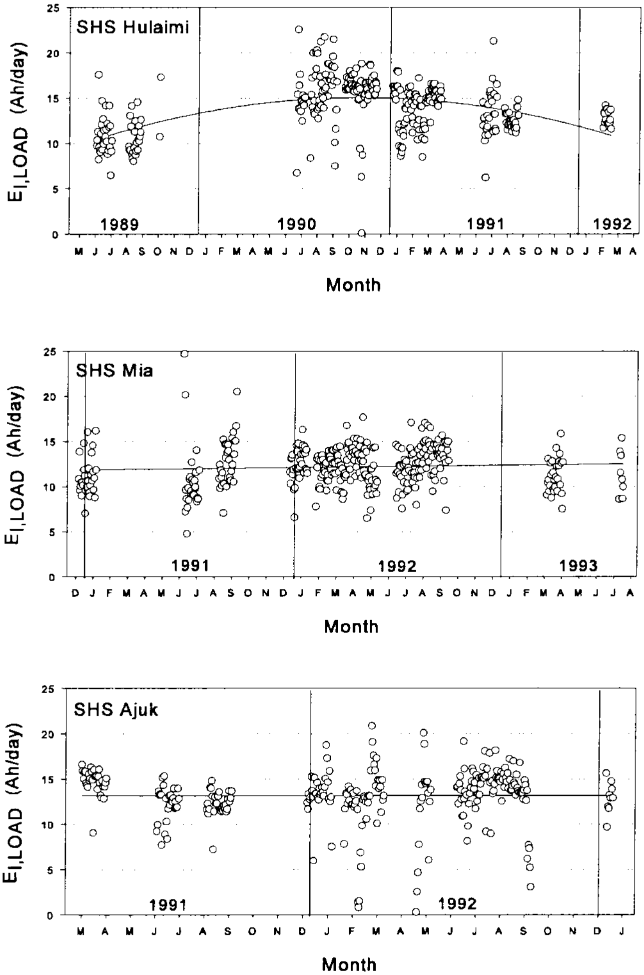

Fig. 11. Time series of the daily electricity consumption $E_{I,LOAD}$ for three SHS in Sukatani for the period 1989–1993. Solid lines indicate a first or second order regression line through all data.

7.4.1. Low irradiance losses

Low irradiance losses are caused by decreased module efficiency at the maximum power point at irradiance below the STC value of 1000 W/m^2. The module efficiency is calculated by means of the two-diode model [42] at a constant temperature of 25°C. The parameters of the two-diode model for the RSM40 PV modules are taken from Van Dijk [43].

Low irradiance losses are indicated in Fig. 12 by $\eta_{25°C} < \eta_{STC}$.

7.4.2. Temperature losses

Module temperatures exceeding the STC value of 25°C cause the PV modules to

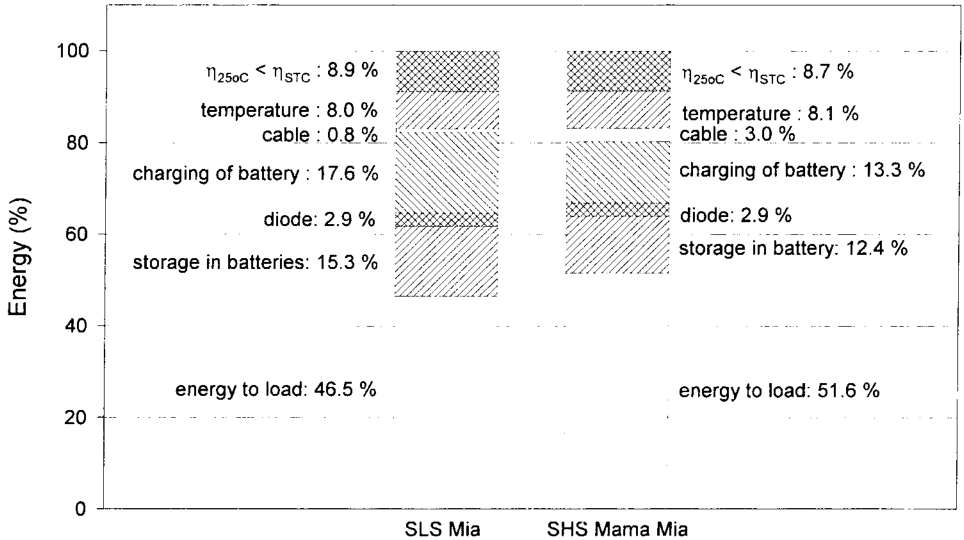

Fig. 12. Energy losses in SLS Mia and SHS Mama Mia with respect to the STC efficiency of 11.1% which is represented by 100% in this figure. Note: energy to the load in percentages equals *PR* based on power and cannot be compared with values of PR_I shown in Table 8.

produce less power; this is called the temperature loss. We calculate the energy effect of elevated temperatures at the maximum power point by means of the two-diode model using the parameters from Van Dijk [43]. The PV module's temperature has not been measured and is calculated by means of the following model [44]:

$$T_M = T_A + kG_{i,ref} \tag{5}$$

where, T_M is the module temperature (°C), T_A is the ambient temperature in the shade (°C), $G_{i,ref}$ is the irradiance in the array plane (W/m^2), and k is the temperature factor (m^2/W/°C).

We use a constant value for T_A of 25°C. This is an accepted approach for the tropical climate in Indonesia [38]. Furthermore, we use a value of 0.03 m^2/W/°C for k, since the PV modules are rack-mounted [44].

7.4.3. DC-cable losses

Cable losses comprise the ohmic losses in the cable between the PV array and the BCR. They are calculated by the following formula:

$$\Delta P_{cable} = RI_A^2 = \frac{2L}{A}\rho I_A^2 \tag{6}$$

where, ΔP_{cable} is the power loss due to the cable (W), R is the resistance of the cable (Ω), I_A is the current from the array (A), L is the length of the cable

between the PV array and the BCR (m), A is the diameter of the cable (m^2), and ρ is the specific resistance of copper (Ωm).

We calculate this energy loss at the maximum power point and use values for L and A given in Table 1 and a value of 1.68×10^{-8} Ωm for ρ.

7.4.4. Losses due to diode

In the BCR a diode is installed over which a voltage drop of 0.6 V occurs. The energy loss due to this diode is calculated by multiplying this voltage drop by the measured current.

7.4.5. Losses due to charging of the battery

Losses due to charging of the battery cover energy losses due to coupling of the PV array with the battery, so that the PV array operates below the maximum power point, and energy losses due to control by the BCR, so that current produced by the PV array will be regulated as soon as the battery is fully charged. Losses due to charging of the battery are calculated by taking the difference between simulated power and the measured power from the array which has been corrected for the effect of the diode in the BCR.

7.4.6. Losses due to storage in the battery

Losses due to storage in the battery are calculated by taking the difference between measured power from the array and measured power to the load.

Results are shown in Fig. 12. Here, 100% represents the STC efficiency of 11.1% of the PV modules. Each energy loss represents a reduction of energy with respect to the STC efficiency. Low irradiance losses and temperature losses are considerable. The biggest energy loss is associated with the charging of the battery: in the case of the SLS and the SHS, 17.4% and 13.3% respectively of the theoretically available energy from the array cannot be fed into the battery because it is fully charged. Here, we also conclude that the PV system is too large considering the average electricity consumption.

7.5. The design of the SHS in Sukatani

In order to evaluate the design of the SHS in Sukatani we execute calculations with the simulation program PVS [45] using measured monthly irradiance data for 1989 [10]. With PVS we searched for the optimum of array and battery size using the specifications of the RSM40 modules [43] and assuming a system autonomy of 4 days. We did this for several hourly load patterns among which those shown in Fig. 3. Furthermore, we assumed that the solar fraction is 95%[12]. The solar

[12] In the design calculations we do not consider the recovery time of batteries. This approach may be very doubtful in climates with a strong seasonal dependency of the irradiation. As this is not the case for Indonesia, we assume that the exclusion of the recovery time in these calculations is acceptable.

fraction, $SF(\%)$, indicates the reliability of electricity supply by the PV system and is defined by:

$$SF = \frac{E_{PV}}{E_D} \tag{7}$$

where, E_{PV} is the electricity produced by the SHS (Wh), and E_D is the electricity demand of the user (Wh).

The results of the design calculations are shown in Table 9.

First, we draw the conclusion that the design load of 216 Wh/day can be met by a battery capacity of 70 Ah. The array size of 80 Wp, as initially installed in Sukatani, would be an appropriate choice for the irradiation measured during the first year of the project which is 4.5 kWh/m^2/day. By using the instruction sheet for the users, we found that under these irradiation conditions a battery of about 40 Ah and a PV module of about 45 Wp could supply the demand for lighting only. Further, in Table 9 it can be seen that the highest demand mentioned in the interviews can not be satisfied with the existing system size assuming an *SF* of 95%. A design with a 130 Wp PV array and a 130 Ah battery may satisfy this demand. A design with a 35 Wp PV module and a battery with an about 35 Ah capacity may be adequate for the user with the smallest consumption. On the basis of design calculations with PVS we conclude that the replacement of the initially installed batteries of 100 Ah by 70 Ah batteries was sensible. Also, we conclude that a broad offer of system sizes may be useful to meet the user's need for electricity.

Table 9
Optimized array size with RSM40 modules and optimized battery capacity calculated on the basis of irradiation H, electricity demand E_D, an autonomy of 4 days and a solar fraction of 95%

Design based on	H (kWh/m^2/day)	D (Wh/day)	$P_{A.nom}$ (Wp)	$C_{I,nom}$ @12 V (Ah)
Real irradiance in 1989, demand according to design calculations, see section 2.1	4.5	216	74	71
Real irradiance in 1989, demand only for lighting according to the instruction sheet	4.5	126	44	42
Real irradiance in 1989, demand for lighting, radio and TV according to the instruction sheet	4.5	170	57	56
Real irradiance in 1989, demand according to user with the largest consumption, see Fig. 3	4.5	390	130	130
Real irradiance in 1989 + demand according to user with the smallest consumption, see Fig. 3	4.5	103	35	34

8. Discussion and conclusions

8.1. The performance of the PV systems

Although it has often been suggested that due to the local mountain climate the irradiation in Sukatani is likely to be less than in the rest of Indonesia [24], we found a value of 4.2 kWh/m^2/day which is normal for Indonesia. Further, monthly variations of irradiation are modest. Hence, the frequently quoted phrase that 'if SHS function in Sukatani they can function anywhere in Indonesia' [24] is an irrelevant remark. Furthermore, it is possible that in the hot season measurements in Sukatani underestimate the irradiation 10% because of soiling of the reference cells with dust. This contamination may also reduce the output of the PV modules.

The failure rate of SLS in Sukatani is high. The main reason for this is an infrastructure problem with regard to the supply and replacement of the TCUs at the end of their lifetimes. Surprisingly, the failure of the SLS does not affect the villagers' positive opinion about this technology.

The monitoring of the PV systems in Sukatani provides values for the PR_{I} of SHS. To interpret our findings we should not compare values for the PR_{I} in Sukatani with values found at other stand-alone PV systems without a back-up generator [46,47,48], because (1) due to the methods applied to the evaluation of monitoring data the PR is not always calculated in the same manner, (2) system sizing may be different and (3) load patterns may differ for different projects. The average PR_{I} in Sukatani is 49%. To interpret this finding we compared the measured value with the design value of the PR_{I}, which is 70%. Here, we conclude that the systems could perform better. The main reason for the discrepancy between the real PR_{I} and the expected PR_{I} is the discrepancy between the electricity consumption according to the design and as recommended on the instruction sheets. The monitored households in Sukatani followed the instructions very well. We found no relation between the daily electricity consumption and the season or the daily irradiation. Further, the low electricity consumption of 11.7 Ah/day was the reason why 100 Ah batteries were mostly replaced by 70 Ah batteries; as a result the batteries could be more fully exploited. Another way of making better use of the battery capacity could have been to give the user an incentive to consume more electricity. The replacement of the original batteries by a smaller type, which is more strongly discharged[13], resulted in an improvement of the ratio of lifetime and costs. The average lifetime of batteries in Sukatani is good compared with other SHS projects in the world: namely 4 and 3.5 yrs for 100 Ah and 70 Ah batteries, respectively, see Table 10.

A section of the initially installed batteries of 100 Ah has been replaced by locally produced automotive car batteries with the same capacity. Although not

[13] On average the 70 Ah batteries will be discharged with a $DDOD = 17\%$

Table 10
Battery lifetimes in Sukatani and according to other research and standards

Reference	Country	Type of battery	Capacity (Ah)	Type of system	Lifetime till replacement (yrs)	Remarks
Sukatani (this research)	Indonesia	Solar batteries	100	SHS of 80 Wp	Average: 4.2 Max: 6.1	
Sukatani (this research)	Indonesia	Locally produced car batteries	70	SHS of 80 Wp	Average: 3.5 Max: 5.8	
Van der Plas and Hankins [6]	Kenya	Locally produced car batteries	n.a.	SHS of 1–200 Wp	Average: 2.4–3.4 Max: 10	90% of the SHS operate without BCR because the majority, 65%, have a power below 25 W
Lorenzo et al. [52]	Bolivia	Locally produced car batteries	120	SHS of 45 Wp	6–9	
Sauer et al. [33]	Germany	Solar batteries	n.a.	Stand-alone PV systems with back-up in kWp range	3–6	European conditions and supervised by research institute
Cabraal et al. [2]	Indonesia	Locally produced car batteries	n.a.	SHS of 50 Wp	3	Used as a rule of thumb in SHS feasibility studies

designed for solar applications, the latter lasted only 3 months less than the so-called solar batteries.

Furthermore, on the basis of data in Table 10 we draw the conclusion that battery performance in SHS under rural circumstances in the Indonesian tropical environment and with the battery installed in the house, does not necessarily deviate from battery performance in Europe[14]. We think that important reasons for this finding are the slight daily discharging of the batteries, instruction of the users and regular control of the batteries during the monthly round of the village technician. Hence, the standard battery lifetime as used in economic calculations of SHS projects [2] could be increased from 3 to 3.5 or 4 years in the case of well-maintained projects.

Considering the set points of the BCRs in Sukatani, we found in 1997 that measured values can deviate by up to 1.2 V. We also found that although the deep-discharge-protection voltage may be too low for Indonesian car batteries [34], so that battery lifetime may be reduced, the realized battery lifetime in Sukatani is rather long. We cannot explain this finding.

According to the design the set points of the BCR should fit to the initially installed Varta battery. However, we don't know how they fit to the batteries installed later.

Therefore, it would be sensible to extend our knowledge on the effects of various set points on batteries in SHS by means of laboratory measurements or systematic monitoring in the field. Furthermore, due to small daily variations of temperature in the battery box, it is not necessary to correct the BCR for the temperature of the battery.

While the average battery size in Sukatani decreased in the course of time, the average electricity consumption increased. On the basis of interviews with users of SHS in 1997 we estimated a 45% increase in the consumption over 5 yrs (with respect to 1992). The average consumption in 1997 compares to the design value of the original system for electricity consumption. In combination with findings from design calculations using the simulation program PVS we suppose that the SHS now are used according to their capability, resulting in a PR_I above 60%.

The simultaneous decrease of strip lights and the growth of small power incandescent lighting in the households indicates the need for very cheap lighting. The presence of dimmed light, like the SBs, may be appreciated above sharp *TL* light for the purpose of social activities. The villagers in Sukatani, however, did not mention such a need. But as a rule, they light a SB during their sleep in the bedroom.

In the case of Sukatani the combination of villagers' own needs and the financial capacity of the villagers leads to a set of appliances other than the

[14] We should be cautious to compare values of battery lifetime for different projects, because (1) end of lifetime is not always defined in the same way, (2) system sizing and, hence, the recovery time for bateries may be different and (3) the type of battery may be different for different projects.

installed standard. For instance, the use of SBs provides the opportunity to distribute the available electricity over more rooms than is possible with three strip lights. Also the use of intercoms is not standard. Thus, generalizing, we think that it would be sensible to reconsider the standardized SHS-concept including only strip lights as appliances. A broad offer of system sizes and appliances may be more successful in meeting the user's need. By means of design calculations we found that PV systems with a battery capacity in the range of 35–130 Ah and a PV module or a PV array in the range of 35–130 Wp are needed to satisfy different demand patterns.

We found that 40% of the SHS users in Sukatani had allowed installation of a connection box to be attached to the grid, although the grid had not yet come to the village. In this manner these people show interest in obtaining a grid-connection. On the other hand, the majority of the users interviewed say they are pleased with the SHS. For both reasons we think that more detailed assessments of the user's preference (an SHS or a grid connection) would be an interesting field for further investigations.

Our general conclusion is that although the design of the SHS systems in Sukatani has been modified in course of time, at present they are in a good state.

8.2. Data collection and analysis of data

Monitoring was done using modest equipment. The monitoring data were useful for analyses on the basis of irradiation and current on a daily or longer basis.

If we want more information about the PV systems, we should follow the guidelines for monitoring given by JRC [49] or IEC [40], which recommend the measurement of (1) power instead of current, (2) power into the battery and from the battery, (3) non-availability of power to the load (only JRC [49])

Monitoring of item (1) and (2) may lead to more accurate analyses and better insight into battery performance. Monitoring of the non-availability of power to the load, can be useful to investigate the reliability of the SHS and the interaction between the user and the system. To obtain useful information on the state-of-charge of the battery, the recording interval needs to be decreased to less than one minute [50].

Also, due to soiling of the reference cells with dust, the measurement of irradiance in the hot season is a matter of concern[15]. On the basis of field experience, we advise cleaning of the surface of the irradiance sensors (and the PV modules) once every 2 days during this period. In the specific case of Sukatani,

[15] Also the accuracy of the calibration of the reference cells is a matter of big concern. We do not have data on the systematic error of the calibration of the reference cells in Sukatani at our disposal, but according to the Dutch working group PV monitoring this error may be 16%. Due to this error measured irradiation could be 16% higher than presented in this paper

this routine could not be executed because of the limited access to the irradiance sensors which were located at the top of the 4-m-high pole which supports the PV panels.

Neither the extension of the set of variables, the reduction of the recording interval or the need to clean the reference cells regularly, answers the need for easy and cheap monitoring in remote rural areas. It would therefore be better to adapt the equipment to the research questions, and not, as happened in our case, vice versa.

Furthermore, in Sukatani 6% of the SHS and 20% of the SLS have been monitored. We don't know the reasons for this distribution. It would make sense to consider the statistics of monitoring before starting a project.

Although only 5 out of 86 SHS have been monitored, the consumption patterns found were assumed to represent the general tendency.We disagree with this assumption. First, monitored households may be more exemplary than the others because they were aware that they were being monitored. Secondly, field research in 1992 [12] and in 1997 proved that there can be a broad range in consumer patterns. Changes in consumer patterns in the course of time can only be understood by results from frequent communication with the villagers and by logbook recordings. These results were not available.

Field surveys should be as effective as possible in order to increase the sample of observed systems and thus enforce the statistical reliability of the results. Therefore, we made a critical study of the usefulness of measurements taken during the field survey in 1997. We made some use of the commissioning procedure of LSDE–BPPT shown in Appendix A. Some of these measurements appeared to be superfluous for our purpose. These are the discharge current, the charge current and the voltage of the battery, because the condition of the battery, represented by the internal resistance, can be determined by these

Table 11
Form to be filled in by an SHS user in the 1997 field survey

	Morning				Day					Afternoon						Evening				Night				
hour	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
Strip light 1																								
Strip light 2																								
Strip light 3																								
Radio																								
Cassette																								
TV																								
Other 1																								
Other 2																								
Other 3																								

measurements only if they are made within the seconds domain. This requirement could not be met with the equipment used in the field survey in 1997.

We did not measure the open circuit voltage of the battery, because the recording is only suitable for determinating the SOC after a wait of some hours [4]. Hence, the condition of the batteries was investigated by measuring the electrolyte density with a hydrometer. In field surveys it is hardly possible to measure the real electrolyte density [50], because due to the limited space in the battery the hydrometer can not penetrate deeply. Due to stratification in the battery the electrolyte density at the top of the battery may be lower than at the bottom [51].

By means of simple hydrometer measurements we can estimate the number of batteries which may fail in the a short term, or we can select batteries for an in-depth measurement of the capacity.

The array current and voltage were measured at the same time as the irradiance. The latter was measured with a portable reference cell. Because it was difficult to orient the sensor correctly and measure the array current and the irradiance simultaneously, our measurements yielded inaccurate results. Therefore, we did not use irradiance measurements in the analysis, and we used the measured array current and voltage to check on the functioning of the PV modules rather than to quantify the performance.

The interviews we conducted were simple. Our choice was determined by the limited time we had available and by the limitation of the research. Additional information could have been of interest; for instance, it would have been interesting to discover how villagers adapt their electricity consumption during the rainy season and to find out how much electricity is supplied by a very low battery. Further it would be interesting to have more detailed information about what happens if a battery is replaced and about how users react to the red light of the BCR.

The combination of an analysis of monitoring data, a field survey and interviews of SHS-users show some contradictions. For instance, on the basis of an analysis of monitoring data we could not conclude whether users had to adapt their electricity consumption in the rainy season. In interviews, howevever, they told us that they did have to do this. [16]. Further, by comparing the number of installed connection boxes for the electricity grid with villagers' answers to the question about the coming of the grid to the village we found that their personal wishes (a grid-connection) did not necessarily correspond to their public request for an SHS.

By comparing the number of installed lights with the lights actually used according to the villagers, we noticed that their answers were influenced by the information given in the instruction sheet.

[16] Notice that monitoring took place at the time when 100 Ah batteries were installed, whereas the questionnaire was completed when these batteries had been replaced by 70 Ah ones. Hence, solar fractions may be different in each case.

Due to deviations between real and narrated experiences, we conclude that a field survey that comprises only interviews may not be sufficient to assess an SHS-project.

Finally, the records of the hourly electricity consumption per appliance may include errors due to users' mistaken time registration and the entwining of actual consumption and imagined consumption. Hence, if we want an accurate and completely reliable registration of the use of each appliance, the best we can do is to monitor the power to each appliance with data loggers. This method also allows to record the daily variation of the load.

Acknowledgements

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Appendix A

Recorded variables during the field survey in 1997

No.	Parameter/variable	Unit
1	System number	–
2	Name of user	–
3	Time	(h)
4	Weather type	(bright sky/cloudy/ overcast/rain)
5	Ambient temperature	(°C)
6	System functions?	(no/yes)
7	Battery type 1	–
8	Capacity battery 1	(Ah)
9	Installation date 1	(mm/yy)

10	Battery type 2	–
11	Capactiy battery 2	(Ah)
12	Installation data 2	(mm/yy)
13	Battery type 3	–
14	Capacity battery 3	(Ah)
15	Installation data 3	(mm/yy)
16	Faulty connection between battery and controller	(no/yes)
17	Battery not in box	(no/yes)
18	Connection load direct to battery (by-pass)	(no/yes)
19	Electrolyte too low >	(no/yes)
20	Specific gravity cell 1	(g/cm^3)
21	Specific gravity cell 2	(g/cm^3)
22	Specific gravity cell 3	(g/cm^3)
23	Specific gravity cell 4	(g/cm^3)
24	Specific gravity cell 5	(g/cm^3)
25	Specific gravity cell 6	(g/cm^3)
26	Charge voltage of battery	(V)
27	Charge current of battery	(A)
28	Discharge voltage of battery	(V)
29	Discharge current of battery	(A)
30	Irradiance	(W/m^2)
31	Current from array	(A)
32	Voltage on array	(V)
33	Status of controller	(original/replaced/broken)
34	Date when controller replaced	(mm/yy)
35	Overcharge-protection voltage of BCR	(V)
36	Charge-reconnect voltage of BCR	(V)
37	Discharge-reconnect voltage of BCR	(V)
38	Deep-discharge-protection voltage of BCR	(V)
39	Unauthorized change of cables	(no/yes)
40	Bad condition of cables	(no/yes)
41	Number of strip lights	–
42	Number of 5 W lights	–
43	Number of fairy lights (<1.5 W)	–
44	Number of radios/cassettes sets	–
45	Number of TV devices	–
46	Connection to the electricity grid	(no/yes/installation available but not connected)

Appendix B

1997 questionnaire

1. Number of the PV system

2. Family name of the household
3. Family size
4. Profession (of the head of the family)
5. What is your opinion about SHS ?
6. What is your opinion about SLS ?
7. Do you speak to other people about the SHS ?
8. If so, what do other people say ?
9. Does the SHS always function/does it often fail ?
10. How does your electricity consumption alter during the rain season ?
11. How do you use and maintain the battery ?
12. Do you know the purpose of the indicator light on the controller ?
13. Do you have enough lights, or do you need more ?
14. Do you want additional appliances like an iron or colour TV ?
15. How many times have you had to replace the lights so far ?
16. Which is better: electricity from the electricity grid or from the SHS, and why ?
17. Will Sukatani be connected to the electricity grid ?
18. If so, when ?
19. Do you want to be connected to the electricity grid ?
20. What kind of light do you prefer: a strip light or a fairy light ?

The form to be filled in by an SHS user is shown in Table 11

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